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Hanford Tanks Initiative Alternate Retrieval System Demonstrations —Final Report of Testing Performed by GreyPilgrim LLC

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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Hanford Tanks Initiative Alternate Retrieval System Demonstrations —Final Report of Testing Performed by GreyPilgrim LLC

Prepared by
GreyPilgrim LLC

Prepared for
Lockheed Martin Hanford Corporation
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GREYPILGRIM LLC

PO Box 3426
Gaithersburg, MD 20885
301.975.4374 fax: 301.921.6165
Pilgrim@GreyPilgrim.com

DATE: 07.15.97

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Robert Kent, VP
GreyPilgrim LLC

GREYPILGRIM LLC
PO Box 3426
Gaithersburg, MD 20885
301.975.4374 fax: 301.921.6165
Pilgrim@GreyPilgrim.com

Final Report of Testing

HTI Alternate Retrieval System Demonstrations
Contract No. MSH-SLD-A31519

Dated: 07.15.97

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS and ABBREVIATIONS

ACTR	Acquire Commercial Technology for Retrieval
BNFL	British Nuclear Fuels, Ltd.
DOE	Department of Energy (USA)
EMMA	Easily Manipulated Mechanical Armature
e-stop	emergency stop (used with control system and power machines)
GUI	graphical user interface
Hz	cycles/sec (Hertz)
ID, OD	inner, outer diameter (of a cylinder or circle)
kpsi	1000 lbf/in^2
lbf	pounds of force (not the same as mass)
LLC	Limited Liability Company
NIST	National Institute of Standards and Technology (USA)
SST	single-shell tank
WTI	Waterjet Technology, Inc.

1.0 INTRODUCTION

A waste retrieval system has been defined to provide a safe and cost-effective solution to the Hanford Tanks Initiative. This system consists of the EMMA robotic manipulator (by GreyPilgrim LLC) and the lightweight Scarifier (by Waterjet Technology, Inc.) powered by a 36-kpsi Jet-Edge diesel powered high pressure pumping system. For demonstration and testing purposes, an air conveyance system was utilized to remove the waste from the simulated tank floor.

The EMMA long reach manipulator utilized for this demonstration was 33 feet long. It consisted of 4 hydraulically controlled stages of varying lengths and coupling configurations. Table 1-1 gives the weight and length of each stage:

Stage	Number of couplings	Length, ft	Weight, lbf
One	4	12	380
Two	2	7	205
Three	3	8	235
Four	2	6.3	155

Table 1-1. Vital statistics of 33-foot EMMA by stage.

Stages One through Three were 24 inches in diameter, Stage Four 18 inches.

The end-effector was mounted on a two-way movable connector allowing the Scarifier to be kept normal to the waste simulant during testing and operation. In addition, the deployment frame to which the manipulator was attached could be moved vertically through five feet of travel, thereby simulating the movement of a deployment mast in a tank environment.

The overall manipulator was 33 feet long and weighed 975 pounds excluding the end-effector. The Scarifier and conveyance hoses added approximately 100 pounds to the manipulator's total weight.

This system takes advantage of the mechanical simplicity of EMMA and the proven performance of the Waterjet Technology end-effectors. This combination of technologies demonstrated its effectiveness in waste retrieval simulations and testing of its ability to withstand the dynamic forces generated by the Scarifier and the waste conveyance system:

1. All electronics and other sensitive components are kept out of the tank, thus ensuring as long a life as possible for the in-tank system.

2. Waste retrieval based on air conveyance leads to an arm lighter in weight, and having less weight offset, than if based on water conveyance. A light arm is more easily and safely deployed through existing Hanford tank risers, thus contributing to system reliability and economy.

3. The heritage of the end-effector and conveyance system enables the development of a full waste retrieval system based on known relationships between subsystems. In this way, most of the waste retrieval system can be designed concurrently with the manipulator. Figure 1-1 shows the end-effector and conveyance hose attached to the arm.

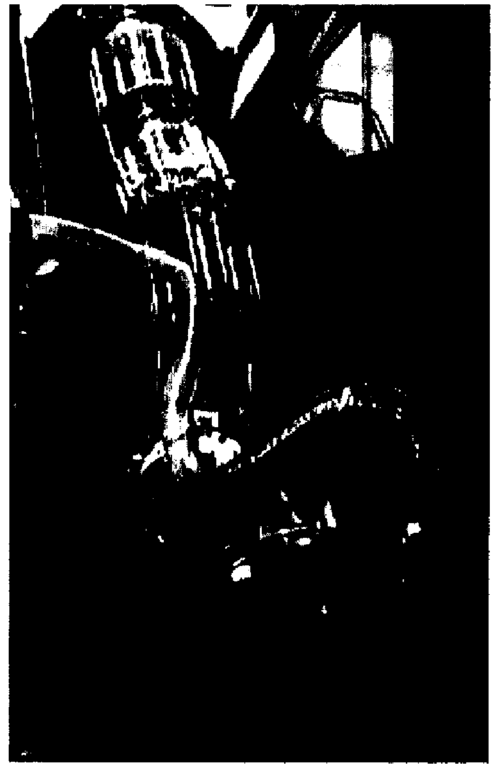


Figure 1-1. Arm with end-effector and conveyance hose.

This system is the result of a collaborative effort on the part of the following team members:

BNFL, Inc.	*Provided overall waste retrieval system design and system integration*
GreyPilgrim LLC	*Provided robotic manipulator technology*
NIST (National Institute of Standards and Technology)	*Provided engineering support and control system design in support of GreyPilgrim's manipulator technology*
Schilling Robotics	*Provided manufacturability support for the manipulator system*
Waterjet Technology, Inc.	*Provided end-effector technology and waste conveyance system support*

Table 1-2. Team members.

Attached to this report is Appendix 5.1, prepared by BNFL, Inc. entitled "Easily Manipulated Mechanical Armature (EMMA) Waste Retrieval System," and dated May 28, 1997. The BNFL report outlines an overall the design concepts of a waste retrieval system to be used for the single shell tank (SST) waste retrieval. Due to the large number of large-format drawings associated with this appendix, it is included only in hardcopy editions of this submission.

An important aspect of the testing documented here is the demonstration of waste retrieval. The team addressed a number of issues during the period leading up to the demonstration. Three major tests were developed to resolve these issues. Those three testing series, and their purposes, were as follows:

ADVANCED STAGE TESTING
- Demonstrate that EMMA will provide sufficient stiffness and load-bearing capability to ensure acceptable waste retrieval performance.
- Provide a component-level understanding of the waste retrieval system.

CONTROL SYSTEM TESTING
- Demonstrate a simple, intuitive operator interface to the waste retrieval system.
- Demonstrate the ability to acquire and hold end-effector position and pointing direction, and to achieve motion trajectories.
- Define and estimate the cost of a control system suitable for Hanford operations.

INTEGRATED RETRIEVAL TESTING
- Demonstrate through IGRIP simulation the deployment of the manipulator into a tank.
- Determine system operating characteristics.
- Demonstrate system flexibility over a range of retrieval scenarios.
- Determine retrieval rate capability.
- Ensure safety and reliability in retrieval process through all aspects of operation.

The issues addressed in these three testing series were as follows:

ADVANCED STAGE TESTING:

Conceptual Design:
1. Can the manipulator long enough to do the job be considered reliable and cost-effective?
2. What is the minimum riser size required for deployment?
3. Can sensitive components be kept out of the tank?
4. Should the conveyance hose run through the center of the manipulator?

Load Bearing & Static Deflection:
5. How well does the system bear static loads caused by end-effector operation at full reach?
6. How accurately can the end-effector be positioned and oriented?
7. Is the system dexterous enough to maneuver around in-tank hardware?

Dynamic Response:
8. How well does the system bear dynamic loads caused by end-effector operation at full reach?

CONTROL SYSTEM TESTING

Operations:
9. Can the system operate under closed-loop control or is telepresence required?
10. Can electronics and actuation be kept out of the tank?

Pointing Accuracy:
11. Can the manipulator "know" where it is within the tank?
12. Can the manipulator be made to avoid in-tank hardware?
13. Can the control system compensate for static deflection of the manipulator?

Dynamic Response:
14. Can excessive vibrations, if induced during operation, be effectively isolated and attenuated by the control system?
15. Can a known end-effector (e.g. Scarifier) be held in a desired position and orientation, and maneuvered along a desirable trajectory?

INTEGRATED RETRIEVAL TESTING

System Deployment & Insertion:
16. Can the in-tank system be delivered into the riser safely?
17. What is the height of the required deployment structure?
18. What structural loads are expected on a tank dome?
19. What hardware is required to process waste outside of the tank?

General Retrieval:
20. What is the expected system life?
21. What is the expected system cost?
22. How long can the system operate before requiring maintenance?
23. Is it cost-effective to jettison a manipulator after failure or completed mission?
24. How will the retrieval system compensate for working in a flammable atmosphere?
25. What is the required head of the retrieval system?

Specific Retrieval Demonstration:
26. Can the system bear dynamic loads caused by waste flow when the manipulator is at full reach?
27. What retrieval rates are achievable?
28. Can water introduced to the tank by retrieval operations be fully scavenged?
29. Can waste be conveyed safely?
30. What maximum size of waste particles can be conveyed?

Failures. The following failures occurred during the testing described here:

- Several storage barrels used to receive conveyed waste and water were imploded during retrieval testing. This was a result of an instantaneous seal being made between the end-effector and cleared surfaces of a waste tray. Those failures are well understood and procedures to overcome them in the future are documented in Section 2.3.2.3.

- A coupling failed during testing of Stage Four prior to waste conveyance and was replaced by a long rigid segment. This failure was due to operator error: load cells were not activated prior to control of horizontal motion in Stage Four, and thus tension was not fed back and could not be limited by the control system. This operator error has been corrected in the control system startup procedure given in Section 2.2.1.2.

2.0 TESTS PERFORMED

GENERAL PROCEDURES FOR ALL TESTS

- All components are labeled with tags. These tags were reviewed prior to each test run to ensure that each component is subjected to an appropriate environment:
    - stage designation
    - weight
    - dimensions
    - weak points (where applicable)
    - operating limits
- Mounted components were checked for proper fastening, symmetry, pre-test damage or deformation.
- End-effector and conveyance hose were inspected for proper functionality.
- Background noise was minimized; lights turned up; non-essential personnel sent away from immediate test area; final safety checks and test announcement made.
- Each test run was videotaped and labeled on-camera.
- Data was recorded in Excel spreadsheets within the immediate test area.
- Qualitative test results (e.g. observations as compared to expectations) were recorded both on videotape and in spreadsheet.
- Digital snapshots were taken as needed for documentation.
- After the test, cables were relaxed; control system user interface and actuator pump turned off; end-effector turned off (where applicable); tags reviewed as needed; and spreadsheet copied to diskette for redundancy.

2.1 ADVANCED STAGE TESTING

The purposes of Advanced Stage Testing were as follows:

- Demonstrate that EMMA will provide sufficient stiffness and load-bearing capability to ensure acceptable waste retrieval performance.
- Provide a component-level understanding of the waste retrieval system.

In this series, EMMA is scaled up to 33 feet in length. Component testing is performed on each stage individually and on multiple stages as part of the integration process. This was done through testing that yielded data confirming component sizing, support structure layout, conveyance hose and end-effector capacity, and interface performance. Conceptual Design issues were addressed by tests performed in other areas.

2.1.1 Load Bearing and Static Deflection

2.1.1.1 Description of Testing

EMMA, as a compliant manipulator, is subject to deflection under static load. As a long-reach manipulator, it is subject to the potential of large bending moments at its interface with a deployment mast. This test was used to characterize deflections and bending moments, and to determine the need for corrective action. This test was also used to examine the extent to which stage curvatures can be dictated by coupling design.

There were therefore two tests performed under this section: Static Deflection and Programmed Curvatures.

2.1.1.2 Test Method and Test Equipment

The following test procedures were followed:

- Measurements of coupling curvature were enabled.
- Measurements of cable tension were enabled.
- Opposite pairs of cables were put in tension to the extent required by the individual test. For motion in a vertical plane, given that only the cable above the load would actually support the load, the cable below would most often be relaxed.
- Manipulator was deployed vertically from above test bench.
- Recorded parameters included individual stage weight and length, static load, individual coupling ID, OD, and active length (where applicable), cable tension, and stage bend angle and direction (where applicable). These parameters served as identifiers for each test run.

Static Deflection:

- Manipulator was extended to maximum horizontal reach.
- Cable tension and individual coupling bends were measured. This step was repeated 30 minutes later, as a measure of static deflection under load. When deflection was measurable, cable tension was adjusted to compensate, and measurements were again made.

Programmed Curvatures:

- Stage was bent by increments to maximum bend angle.
- Cable tension and individual coupling bends were measured. This procedure was repeated for each stage.
- Coupling bends for each stage were compared to expected behavior, to determine to what extent stage curvature was predictable for this arm.

The following data was recorded in these tests:
- cable tension for the uppermost cables in each stage
- payload weight
- linear deflection

The following equipment was used:
- dead weights for static load (not the Scarifier)
- light pen
- target (at times a dartboard, possibly more compelling than any other target)
- level or protractor

The following safety precautions were taken:
- Make sure that the dead weights don't fall on toes.

The following were considered to be final products:
- linear deflection as a function of payload weight and elapsed time
- cable tension necessary to compensate for deflection

These tests were performed with the arm positioned in its 17-foot maximum horizontal reach.

The following procedures were followed prior to the test:
- Designate a data taker.
- Prepare the target, and hang it a reasonable distance from the arm, and normal to the pointing direction of the arm. Mount a light pen on the arm, pointing parallel to the arm's axis at the end-effector position, and position the target such that the light pen is on the bullseye. Verify, using level or protractor, that the light pen is pointing horizontally.
- Choose static loads (not the Scarifier) and find a way to mount them securely near the end of the arm.
- Understand the geometry of the test setup:

  - **L** is the distance of the light pen from the bullseye
  - **theta** is the angular deflection of the end of Stage 4 due to the load
  - **d** is the deflection of the beam from the bullseye (ostensibly straight down, though if you don't start perfectly horizontal and balanced there could be a little torsion)
  - **delta** is the actual static deflection of the light pen itself

- The geometry is such that delta = d - L sin(theta).

The following procedure was followed during the Static Deflection test:
1. Orient arm so light pen points horizontally.
2. Wait 30 minutes to allow arm to sag.
3. Measure d and theta. From these, determine delta.
4. Apply load.
5. Repeat 3.

The following procedure was followed during the Programmed Curvatures test:

1. Measure the horizontal position of the CG of each coupling and segment with respect to the vertical axis of the manipulator origin.
2. Compare to what those positions would be if each stage's couplings shared the bend of the stage equally.

2.1.1.3 Test Results

Static Deflection. With the arm extended to its maximum horizontal reach of 17 feet, 2500 lbf of cable tension was necessary in Stage Four's uppermost cable to hold the end-effector's horizontal position. (The control system was set to limit Stage Four tension to 3000 lbf.) After this position was achieved, the arm was allowed to remain in position for 30 minutes. The static deflection resulting from this 30-minute delay was 1.8 inches. After the delay was completed, a 50-lbf dead weight was hung from the arm at the end-effector position. This resulted in another 0.6 inches of static deflection.

The deflection due to the extra static load was overcome by increasing the cable tension in the uppermost cable from 2500 to 2700 lbf. The deflection due to sag was overcome by increasing cable tension from 2700 to 2900 lbf. In other words, 2.4 inches of static deflection, possibly due to static loading on the entire arm, were fully correctable with one cable in one stage, and with margin remaining in that stage's uppermost cable.

As a means of examining static deflection behavior in the entire arm, measurements of cable tension were taken as a function of arm position. These measurements are also useful in verifying that stages are statically decoupled. Repeated measurements are used to determine statistical mean and standard deviation of tension in cables not directly used for position control.

The position of Stage Four was varied vertically over 20 degrees peak-to-peak, and horizontally over 50 degrees peak-to-peak. Stage Four was biased slightly to the right to examine differences in the tension seen in opposite pairs of cables. Seven positions were investigated, with the following observed results:

- Stage One tensions varied with position only in the left cable, as tension increased when Stage Four was pulled to the left. (average 9000 lbf, standard deviation 200 lbf)
- Stage Two tensions varied with position only in the uppermost cable, as tension was highest when Stage Four was moved in the vertical plane. (average 5400 lbf, standard deviation 100 lbf)
- Stage Three tensions varied with position only in the left cable, as tension was highest when Stage Four was moved in the vertical plane. (average 2500 lbf, standard deviation 200 lbf)
- Stage Four tensions varied as follows:
    - The cable doing the pulling nearly always showed the greatest tension. In each case, the opposite cable was seen to relax measurably.
    - Each cable's tension was always within the preset 3000 lbf tension limit for the stage.
    - The arm was biased toward the right. Measured values of tension followed this bias.

- For motion in the horizontal plane, the lower cable remained at 700 lbf, and the upper cable at 2500 lbf. For motion in the vertical plane, the lower cable averaged 1300 lbf with a standard deviation of 1000; the upper cable averaged 1900 lbf with a standard deviation of 1000.
- For motion in the vertical plane, the left cable remained at 1000 lbf and the right cable at 1300 lbf. For motion in the horizontal plane, the left cable averaged 1400 lbf with a standard deviation of 900; the right cable averaged 1600 lbf with a standard deviation of 700.

The 3000 lbf tension limit programmed into the control system was insufficient to pull Stage Four much further than the maximum peak-to-peak bends indicated for this test, but those maximum bends were ample for Integrated Retrieval testing, and were effective in a limited demonstration of obstacle avoidance.

The control system displays of tension reflected reliable feedback from the load cells. Motion of Stage Four appeared to cause reactions in the other three stages, but when Stage Four is stationary, it is almost completely statically decoupled from each of the other three stages, based on the small standard deviation of tension in all other cables. This is a sign of the effectiveness of conduit in isolating stage motion.

<u>Programmed Curvatures</u>. There are two opposing phenomena that must be taken into account when sizing couplings: first, couplings as they progress outboard have decreasing weight moment, which indicates increasing control authority; second, tension is lost in bushings as the stage bends, which indicates decreasing control authority. These two behaviors, when well-understood, can be balanced to provide an accurate prediction model of stage curvature, under the following conditions:

- The curvature has to be designed with the primary plane of motion in mind, since gravity effects weight moment differently in different planes, and the curvature seen in a vertical plane is likely not be the same as that seen in a horizontal plane as a result.
- The desired curvature is likely to hold only over a limited range of stage bend, outside of which one or the other of the two opposing phenomena mentioned above will dominate motion.

Prediction models still need a great deal of development.

In the case of this test, observations appeared to indicate that for each stage, each coupling would bend an equal amount over the entire stage bend. This was clearly seen in the eight-foot ACTR arm, and was expected here. In retrospect, the larger size of this arm and the larger static loads associated with it make the possibility of equal sharing of stage bend remote without some variation in individual couplings, which was not pursued here.

With the arm extended to its full 17-foot horizontal reach, the horizontal distances to the center of mass of each coupling and each rigid segment were measured. With these distances, simple geometry was used to determine the most likely stage bends to deliver that data. The observed results are as follows:

- Stage One (34 degrees): first coupling 4, second 7, third 12, fourth 11
- Stage Two (22 degrees): first coupling 8, second 14.
- Stage Three (34 degrees): first coupling 12, second 11, third 11.
- Stage Four (0 degrees): stage fully extended horizontally.

Note: the coupling bends of Stage One indicate the largest attempted due to space limitations.

For an observer with unaided eye on the floor below the arm, this orientation appears to have almost equal sharing of stage bend among the couplings, especially in Stage Three. The test showed, however, that the decreasing static load on each coupling moving outboard from a stage's origin was dominant in determining how Stages One and Two would actually bend.

No couplings were observed to have failed, and the arm was developed with test area spatial limitations clearly in mind. This test shows that it is possible to develop couplings that give a desired curvature, though that was not actually done for this arm.

The following table indicates maximum capabilities attempted with this arm during this testing:

Arm Orientation	Stage Bend (deg)	Coupling bend (deg)	Static load (lbf)	Max tension (lbf)
max horizontal reach	Stage One: 34	4, 7, 12, 11	700	9000
	Stage Two: 22	8, 14	500	5400
	Stage Three: 34	12, 11, 11	250	2500
	Stage Four: 0	0, 0	100	2800
max sideways reach	Stage One: 34	4, 7, 12, 11	700	9000
	Stage Two: 22	8, 14	500	5400
	Stage Three: 34	12, 11, 11	250	2500
	Stage Four: 20	8, 12	100	2500

Table 2-1. Maximum reach, bend, load, and tension characteristics.

2.1.2 Dynamic Response

2.1.2.1 Description of Testing

A shorter version of EMMA was previously tested in vibration environments in the ranges of 0.1-1.0 Hz and 10-80 Hz. An in-tank system used for service should be capable of absorbing or rejecting disturbances in the frequency range of 0.05 to 100 Hz. This capability must hold for any curvature the manipulator is likely to take assume during tank operations. This test was used to verify the desired capability, and to determine the need for corrective action.

The Scarifier was considered suitable for dynamic response testing, in that it could be spun at frequencies close to those predicted as natural frequencies for the arm. Under high pressure water flow (10 to 30 kpsi) as needed for Integrated Retrieval testing, the manipulator showed no observable steady-state vibrations, and transient vibrations when observed were always at low frequency. There were then two questions left unanswered by Integrated Retrieval testing:

- What is the frequency range for this manipulator?
- Is it possible for the Scarifier to excite the arm in this range?

During retrieval demonstrations, the arm was observed to have residual vibrations after getting momentarily stuck on, and then unstuck from, the waste surface.

There were therefore two tests performed under this section: Free Vibration and Steady-State Response.

2.1.2.2 Test Method and Test Equipment

The following test procedures were followed:

- Measurements of vibration amplitude were enabled.
- Manipulator was deployed at its 17-foot maximum horizontal reach.
- Recorded parameters included individual stage weight and length, static load, individual coupling ID, OD, and active length (where applicable), cable tension, and stage bend angle and direction (where applicable). These parameters served as identifiers for each test run.

Free Vibration:

- Control system was prepared through procedure given in section 2.2.1.2.
- Targets were put in place for examination of repeatability.
- Control system was used to start motion of arm in horizontal plane, and stop arm in such a way that light pen would point as near to the target as possible without repositioning. (The sudden stop was expected to generate residual vibrations at the arm's natural frequency.)
- A timer was started with the stop command to the arm. It was allowed to run until residual vibrations ceased.
- Peak-to-peak deviations from the target were marked and noted.
- The peak-to-peak deviations and elapsed time were used to determine arm natural frequency. The log decrement method was applied to deviations to determine damping ratio.
- This procedure was repeated for repositioning of Stages Two, Three, and Four.

Steady-State Response:

- Excitation was enabled and set at frequency in desired range.
- Measurements were taken of cable tension, vibration amplitude, and pointing offset (where applicable). When deflection or pointing offset were large, frequency was noted. Such frequencies were assumed to be at or near structural modes.

- Frequencies at which deflection or pointing offset was large were repeated, with an attempt made to compensate for that motion by adjustments in cable tension.

The following data was recorded in these tests:
- rotation of the stage
- position of the light pen relative to a target

The following equipment was used:
- light pen
- target (the dartboard was used in the Steady-State Response test)
- level or protractor

The following safety precautions were taken:
- Wear a hard-hat if under the arm.
- Be careful climbing around on the arm.

The following were considered to be final products:
- Repeatability of position for each stage
- Comparison of test data to predictions of performance

The following procedures were followed prior to the test:
- Assign a data taker.
- Mount the target a reasonable distance from the arm, and normal to the pointing direction of the arm. Mount a light pen on the arm, pointing parallel to the arm's axis at the end-effector position, and position the target such that the light pen is on the bullseye. Verify that the light pen is pointing horizontally.

Free Vibration:
- Choose several positions of the stage to examine, based on the bending capability and maximum allowable (by the control system) tension of the stage.

Steady-State Response:
- Enable city water to the Scarifier.
- Adjust Scarifier spin rate to a range suitable for excitation.

2.1.2.3 Test Results

Free Vibration. Stages Two, Three, and Four were alternately slewed through the equivalent of a sweep across a waste surface and stopped suddenly, inducing a free vibration impulse response on the arm. The following results were obtained:

- Stage Two: max peak-to-peak 2.6 in; natural frequency 0.5 Hz, damping ratio 20%.
- Stage Three: max peak-to-peak 2.4 in; natural frequency 0.7 Hz, damping ratio 10%.
- Stage Four: max peak-to-peak 1.9 in; natural frequency 0.5 Hz, damping ratio 10%.

These results indicate that the vibration response is not strongly affected by the stage excited for an arm of this length in the given position.

Steady-State Response. The Scarifier, unfortunately, was not equipped to deliver frequencies as low as 0.5 Hz and thus could not be used to excite the arm directly at its natural frequency. It was limited by the accuracy of its motor to frequencies no lower than 1 Hz. Furthermore, an internal sensor malfunction left the Scarifier unable to achieve natural frequencies higher than 5 Hz.

A dartboard was placed just beyond the Scarifier along the arm's axis, and a light pen attached to the arm. With city water flowing at 4.5 ft3/min, the spin rate of the Scarifier was slowly adjusted between 1 and 5 Hz, with the dartboard centered such that the light pen pointed toward the bullseye. The light did not leave the center of the bullseye at all, even by an amount as small at 1/16 inch (assumed to be the smallest amount observable). Although the case can be made that city water pressure isn't enough to impart a great deal of energy to the arm, it's also evident that the end-effector of choice can't excite the arm by any means under which it is likely to operate in service.

2.2 CONTROL SYSTEM TESTING

In this series, operation of EMMA was examined with an automated control system. The control system consists of the following components:

- data acquisition and computer control
- improved joystick design
- numerical inverse kinematics
- trajectory design
- sensory feedback

This was done by performing tests that yielded data on control system performance, pointing accuracy, and dynamic response. The purposes of Control System Testing are as follows:

- Demonstrate a simple, intuitive operator interface to the waste retrieval system.
- Demonstrate the ability to acquire and hold end-effector position and pointing direction, and to achieve motion trajectories.
- Define and estimate the cost of a control system suitable for Hanford operations.

2.2.1 Pointing Accuracy

2.2.1.1 Description of Testing

The control system must be designed to correct for sources of uncertainty in position and pointing accuracy such as coupling nonlinearity, static deflection, disturbances, and measurement error or failure. The available actuation must provide sufficient control authority to compensate for each source of uncertainty as it arises; and the controller, whether totally automated or telepresent, must exploit that control authority. This test was used to verify the desired capability, and to determine the need for corrective action or design changes.

We know already that larger actuators would give greater control authority. This is the first step in determining the resources required for the control system to implement full-order closed-loop control.

There were therefore two tests performed here: Target Acquisition and Obstacle Avoidance. The test for Target Acquisition was performed both experimentally (with the actual arm) and analytically (with a numerical model of the arm and the inverse kinematics technique under development).

2.2.1.2 Test Method and Test Equipment

The following test procedures were followed:

- Measurements of static deflection were enabled.
- Measurements of pointing offset were enabled.
- Measurements of cable tension were enabled.
- Manipulator was deployed vertically from above test bench.
- Recorded parameters included individual stage weight and length, static load, individual coupling ID, OD, and active length (where applicable), cable tension, and stage bend angle and direction (where applicable). These parameters served as identifiers for each test run.

The control system is set up with the following procedure:

- Check pump, actuators for leaking fluid. Delay operation until problems are resolved if any are found.
- Activate pump.
- Activate control system electronics and load cells.
- Check conduit for kinking; couplings for discontinuities. Delay operation until problems are resolved if any are found.
- Call up EMMA controller user interface within LabWindows/CVI on PC.
- Enable manual joystick control.
- Release manipulator from restraints.
- Check system again for any unusual sights or sounds.
- Operate manipulator.

Target Acquisition:

- A target was established for the end-effector to reach.
- A static load was located at the end-effector position.

- Manipulator was commanded through a predetermined trajectory to acquire the target, and operator was cautioned not to slow down, but rather to acquire the target as quickly as possible.
- Target acquisition was repeated through other trajectories.

Obstacle Avoidance:
- An obstacle was placed between a starting position and the target, and target acquisition was performed with predetermined obstacle avoidance maneuvers.

The following data was recorded in this test:
- Tension in each cable bearing primary load. In most cases, that's one per stage.
- Stage bend for each stage.

The following equipment was used:
- light pen
- target
- timer

The following safety precautions were taken.
- Wear a hard-hat if under the arm.
- Don't go climbing around on the arm.

The following were considered to be final products:
- Plots of cable tension v. position (or position error)

The following procedures were followed prior to the test:
- Designate someone to be "Clipboard Man." Designate someone else to be "Timer Man."
- Prepare the target and light pen in such a way that the light pen will hit the target when the trajectory is completed. (Use a practice run if necessary.)
- Establish a trajectory for the arm for each test.

2.2.1.3 Test Results

The performance of the control system for the 33-foot arm under manual/telepresent control was better than expected. The performance of the inverse kinematics algorithm was also quite good. These results lead to high confidence in the ultimate development of a fully automated capability.

Target Acquisition. The arm was first operated across a sweeping motion similar to that used during retrieval testing. At the end of each sweep the control system was used to stop the arm and the position of the light pen marked on paper to examine accuracy and repeatability. Under manual control, the arm can be made to achieve arbitrarily small accuracy; but in this case, the operator slewed the arm and was given only one chance to stop the motion and try to hit a small target (that being the last position of the light pen when stopped. This was done for three sets of passes.

- First pass: average distance between end positions one inch (equal parts horizontal and vertical error).
- Second pass: average distance 1.5 inches.
- Third pass: average distance 1.25 inches.

For this test, the operator had a minimum of training, and was able to repeat positions to within 1.5 inches after a slew at the same translational rates used for retrieval and only one chance to hit the target, without slowing down.

The inverse kinematics algorithm was tested with a mathematical model of the arm moving in a plane in much the same way as the actual arm. Two stages of this mathematical model were to be moved through a distance of 8.5 inches, with no change in the end-effector pointing direction. The algorithm performed the calculation of joint angles for this move in less than one second of computing time to achieve an accuracy of less than one-tenth of an inch. Figure 2-1 indicates the path taken by the algorithm to achieve a solution, in terms of end-effector Y-position v. X-position (motion in a horizontal plane):

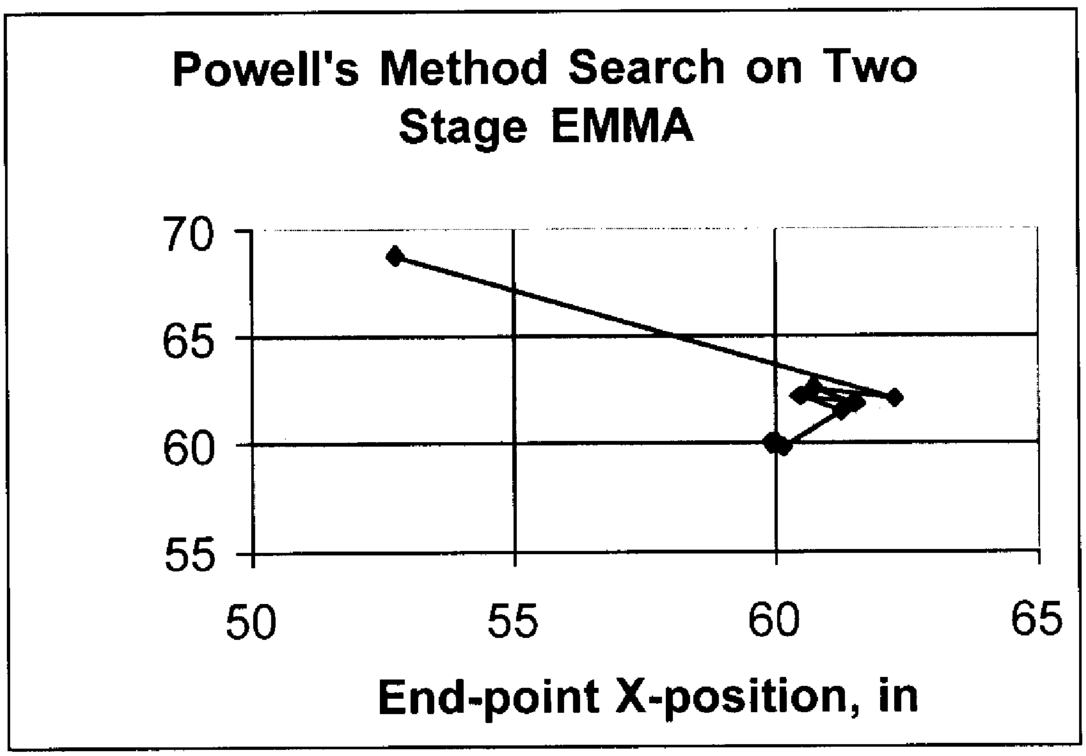


Figure 2-1. Some inverse kinematics testing results.

As more stages become involved in a move of the end-effector, the algorithm of course becomes slower, though there is a tradeoff between computational speed and final position accuracy.

The implementation of inverse kinematics to the control system includes the following individual jobs:

- Determine or prompt user for basis directions for line search
- Determine or prompt user for order in which directions are followed
- Determine step size
- Actually search in direction that decreases objective function
- Determine when search direction has been fully exploited; change direction; calculate new direction at appropriate conditions
- Determine when search is completed; verify position and pointing direction
- Determine or prompt user for number of discrete points in some motion trajectory

This is a significant effort, and may require the off-line implementation of the algorithm for any but the simplest moves.

Obstacle Avoidance. A cylindrical object was placed such that a sweep trajectory like those used for retrieval would bump the object. The operator slowed the arm down and through the use of Stages Three and Four, and the end-effector pivot, avoided the obstacle.

The obstacle overlapped the basic sweep path first by one inch, then by three, then by four inches. The arm was made to avoid the obstacle without contact each time. Figure 2-2 illustrates the arm about to undertake an avoidance maneuver.

This was done with a 20-degree peak-to-peak vertical motion limitation placed on Stage Four, and with no participation from Stages One or Two at all.

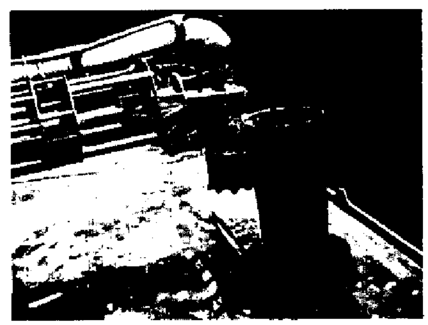


Figure 2-2. Obstacle avoidance

With the use of more than two stages and/or the elevator, more substantial obstacles should be avoidable, and this testing is ongoing.

2.2.2 Dynamic Response

2.2.2.1 Description of Testing

Although no problem in vibration response was detected in previous testing, large structural vibrations increase in likelihood with the length of the manipulator. The response of a moving manipulator to end-effector operation also must be understood. The available actuation must provide sufficient control authority to compensate for each source of uncertainty as it arises; and the controller, whether totally automated or telepresent, must exploit that control authority. This test was used to verify the desired capability, and to determine the need for corrective action or design changes.

The same procedure as that used in test 2.2.1 was followed again in an attempt to induce some residual vibration and attenuate it through control.

2.2.2.2 Test Method and Test Equipment

The following test procedures were followed:

- Measurements of static deflection were enabled.
- Measurements of pointing offset were enabled.
- Measurements of cable tension were enabled.
- Manipulator was deployed vertically from above test bench.
- Recorded parameters included individual stage weight and length, static load, individual coupling ID, OD, and active length (where applicable), cable tension, end-effector operational frequency (where applicable), control method (e.g. joystick or GUI), and stage bend angle and direction (where applicable). These parameters served as identifiers for each test run.

The following related activities were also performed:

- Development of forward kinematics consistent with previous test results.
- Selection of numerical method ("Powell's Quadratically Convergent Method") to solve for the minimum of an objective function based on position, with a constraint on pointing error. This method is outlined in the Appendix.
- Estimate of personnel effort required to code method into controller console v. effort required to perform method off-line and prepare results as a table look-up.

The following data was recorded in this test:

- Tension in each cable that's bearing load. In most cases, that's one per stage.
- Stage bend for each stage.
- Cable travel for each stage.

The following equipment was used:

- light pen
- target (dartboard OK, though waste tray would be better for images, provided it would not be in the way)
- timer

The following safety precautions were taken:

- Wear a hard-hat if under the arm.
- Don't go climbing around on the arm.

The following were considered to be final products:

- Plots of cable tension v. position (or position error)

The following procedures were followed prior to the test:

- Designate someone to be "Clipboard Man." Designate someone else to be "Timer Man."

- Prepare the target and light pen in such a way that the light pen will hit the target when the trajectory is completed. (Get the target in the right place. This could take a practice run.)
- Activate control system with procedure outlined in Section 2.2.1.2.

2.2.2.3 Test Results

In test 2.2.1, and in retrieval, it was observed that momentary setbacks or sudden stops in arm motion would lead to residual vibrations. These vibrations would generally take on the characteristic observed in the free vibration response mentioned in 2.1.2: a natural frequency of about 0.5 Hz, lightly damped (10 or 20%), and a peak-to-peak vibration of about 2 inches or so. This residual vibration is unacceptable for service unless it can be controlled.

The neutral position of the joysticks, designed to stop motion at the last commanded position, was not actually stopping motion: the motion would continue until naturally damped out. The operator found that this could be compensated for with the joystick by actually commanding the joystick to move modestly in the opposite direction until the original motion had stopped. This is analogous to a driver letting up on a car's brake as the car approaches a stop sign. This way, the operator was able to cancel residual vibration, though timing this action was difficult, and thus would not be reliable if the arm were in a teleoperative mode.

But a simpler means of control was found: the command in the GUI to stop motion was originally designed to zero out commands to the control law algorithm. The system, however, would continue to respond to preexisting error. The control loop can be broken in a better place for accuracy! The arm positioning sequence was tested again, this time with the e-stop used to stop motion rather than the stop command in the control law algorithm. The e-stop breaks the control loop between the control law algorithm and the actuators. With no command to the actuators, motion comes to a complete stop at the instant the e-stop is invoked, and with no observable residual vibration at all.

Future generations of the control system will include a stop command that zeroes out actuator input.

2.3 INTEGRATED RETRIEVAL TESTING

In this series, advantages to an in-tank system using EMMA, previously understood qualitatively, were examined quantitatively to enable planning for future tank operations. Specifically, this series of tests examined the promise of minimized conveyance hose bending (leading to higher efficiency, lower wear, and lower dynamic loads). This was done through testing that yielded data on retrieval rate and quality, pointing accuracy, and dynamic response. The purposes of Integrated Retrieval Testing are as follows:

- Determine system operating characteristics.
- Demonstrate system flexibility over a range of retrieval scenarios.
- Determine retrieval rate capability.
- Ensure safety and reliability in retrieval process through all aspects of operation.

Figure 2-3 illustrates the arm at its 33-foot testing length:

Figure 2-3. The 33-foot EMMA.

2.3.1 System Deployment

2.3.1.1 Description of Testing

NIST and GP developed a conceptual design interface between EMMA and a deployment mast. The interface was designed with the following goals in mind:

- Simple connection and disconnect between the mast and EMMA.
- Accommodation of manipulator shielding.
- Delivery to a variety of risers, and at a variety of angles of attack.

A support structure was designed and built which enabled vertical deployment of the first stage of the manipulator above a tray of waste, and which allowed subsequent stages to conduct operations on the waste. This test was used to verify site safety, and to assist in assessing deployment options for the Hanford tanks.

There were therefore two tests performed here: Physical Deployment and IGRIP Simulation.

2.3.1.2 Test Method and Test Equipment

The following test procedures were followed:

Physical Deployment:

- Manipulator was deployed vertically from above test bench.
- Develop an "elevator" to act as a mast, offering vertical motion.
- Prepare alternative designs for an actual tank deployment structure.

IGRIP simulation:

- Develop a simulation of the deployment and retrieval processes.
- Employ models of Hanford tank interiors.
- Employ NIST models of teleoperative crane devices and of the manipulator proposed for simulated retrieval.

2.3.1.3. Test Results

Physical Deployment. A deployment system was developed for use in simulated retrieval. It consists of the following components:

- An "elevator" that allows the arm to be raised and lowered vertically by means of a crane: the elevator is guided in a straight line by wheels braced against structural supports in the room above the High Bay Alcove (referred to as the Actuator Room).
- A truss structure of sufficient strength to mount the four actuators responsible for the control of Stage One, and which conveys conduit for the other three stages from their actuators into the arm.
- A support structure for the other 12 actuators.
- A one-degree-of-freedom cable-driven pivot for the end-effector.

The crane which supports the elevator is located another floor above; the manipulator and deployment system now occupy three floors adjacent to the High Bay.

The deployment system was used successfully to move the arm up and down, and was regularly involved in repositioning the arm for passes along the waste surface during simulated retrieval. At no time were loads passed through the arm to the truss structure sufficient to impede vertical motion capability. At no time were vibrations passed along the arm from the end-effector observable in the truss structure. (This usage addressed Issue 16.)

The end-effector pivot was also useful in extending the capability of the manipulator: as the end-effector position is raised and lowered, the pivot enabled the Scarifier to be held normal to the waste surface. This capability was not used often during simulated retrieval, because of the limited range of motion required to access waste simulants, but when used was always effective.

Limitations of the Deployment System. Although this system was never intended to serve as a "scale model" of one used for waste retrieval at an actual underground storage tank, it did provide valuable lessons that can be applied later. Here are some limitations faced by the system described here:

1. The ceiling of the Alcove is too low for a 33-foot manipulator to become fully extended in the vertical direction, and the range of motion of the elevator was not sufficient to make up the difference.
2. The opening from the Actuator Room to the Alcove was partially blocked by small crane equipment, which did not allow for a full bend of Stage One. Since Stage One could neither be fully bent or fully extended, it could not participate substantially in simulated insertions/extractions. Further, the constant partial bend assumed by Stage One imparted risk of limited life to the couplings in the stage. For these reasons, Stage One was not repositioned very much during retrieval.
3. The Actuator Room was too small to permit a smooth, gentle curvature of conduit for Stages Two through Four. As a result, tension losses in those stages were likely much greater than should be expected during service. Conduits also frequently became kinked, requiring the use of splints to extend their lifetimes. Soon after this testing is completed, they will all require replacement.
4. The pivot could have been exercised more rigorously, perhaps by testing retrieval in an elevated waste tray.

There were no excessive moments passed through the manipulator to the elevator structure, as judged by the smooth vertical motion always available, even with the arm fully extended.

None of these limitations presents a new issue to be resolved. Their solutions are clear and clearly achievable. It only serves as a starting point, however: Hanford tanks offer no structural members for a deployment mast to brace against.

IGRIP simulation. An IGRIP simulation was used to demonstrate potential deployment and retrieval concepts. Existing models of the manipulator and of a mobile crane were combined to examine deployment and retrieval issues. The simulation was not completed to a high level of fidelity, but was (and still will be) useful in trade studies both on cranes and on the arm. Figure 2-4 illustrates the arm in a tank and deployed from a NIST robotic crane.

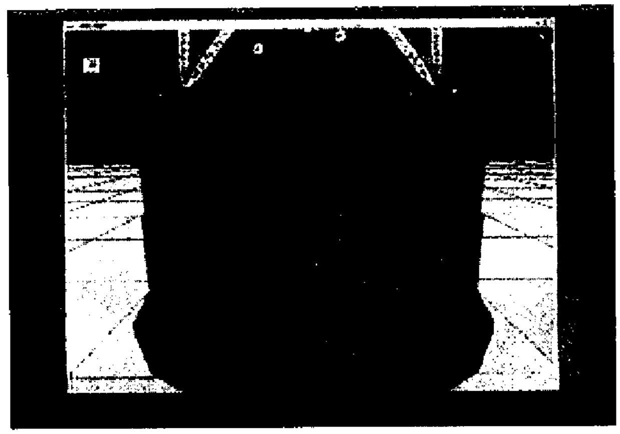


Figure 2-4. IGRIP simulation.

The primary limitation in the simulation at present is that the arm model is only able to exhibit preprogrammed motions. Since the development of inverse kinematics has been conducted in parallel to this effort, it was not possible to integrate inverse kinematics into the simulation during this testing; and appropriate trajectories for the arm are also still under investigation and thus could not be preprogrammed extensively.

Nevertheless, the IGRIP simulation has helped in the following lessons learned for retrieval systems based on EMMA's available degrees of freedom alone:

- Any planar trajectory more complex than a "windshield wiper" type of motion, if the end-effector is to hold orientation, requires the participation of at least three manipulator stages. This is because any stage restricted to move in a plane has only one degree of freedom in motion (the "windshield wiper"), and a planar trajectory that holds orientation requires three degrees of freedom.
- A planar trajectory in which both the end-effector's orientation and its position in one direction must be held will require a "snap-through" of one or two stages (i.e. a near-instantaneous change from some curvature of the stages to the "mirror image" of that curvature). This is avoidable through the use of a fourth stage to move the curvature momentarily out-of-plane, or through the use of extra degrees of freedom not available in the arm in and of itself.
- To achieve a constant translational rate in a planar trajectory with closed-loop control may require a nonlinear feedback algorithm or table lookup to take advantage of the nonlinear relationship between stage bend angular rate and end-effector translational rate.
- Requirements on accuracy of end-effector orientation and on translational rate will determine to what accuracy (i.e. with how many points) the trajectory must be defined. The more points needed to define the trajectory, the greater the burden on the control system duty cycle. One means of simplifying this problem is to calculate trajectory points (and probably joint angles to achieve them) off-line.

2.3.2 Waste Simulant Retrieval

2.3.2.1 Description of Testing

There are several issues documented here that could not be addressed by any means other than waste retrieval. Retrieval, when attempted, enables designers to determine the expected life of the in-tank system under actual service.

This test was used to verify that waste simulants could be removed, and to determine the need for corrective action or design changes.

2.3.2.2 Test Method and Test Equipment

The following test procedures were followed:

- Measurements of static deflection were enabled.
- Measurements of pointing offset were enabled.
- Measurements of cable tension were enabled.
- Measurements of waste flow were enabled.
- Measurements of water pressure were enabled.
- Manipulator was deployed vertically from above test bench.
- Recorded parameters included individual stage weight and length, static load, individual coupling ID, OD, and active length (where applicable), initial cable tension, end-effector operational frequency (where applicable), control method (e.g. joystick or GUI), waste simulant (sludge or saltcake), and initial stage bend angle and direction (where applicable). These parameters served as identifiers for each test run.
- A trajectory within the waste tray was established for the end-effector to achieve.
- The control system was enabled via the procedure given in Section 2.2.1.2.
- The end-effector was enabled at a predetermined operational mode and frequency.
- The manipulator was commanded to reach the waste surface, and waste was retrieved.
- The procedures given here were repeated for various combinations of simulants.
- During retrieval, observations regarding the status of the manipulator, conveyance system, end-effector, and waste collection reservoir were recorded.
- After retrieval, assessments of the condition of all components were taken to enable predictions of system life and cost.
- BNFL was called upon to list the steps required to go from successful demonstration to a retrieval-ready system.

A waste conveyance system featuring the Scarifier was designed by WTI for this test. A vacuum air conveyance system was used, which consists of the following components:

- blower: 1000 cfm @ 12.9 psia inlet, 14.7 outlet; 15 HP, 1800 RPM, three-phase motor
- cyclone: 14g, carbon steel
- hose: 4" OD, approximately 50 feet in length

This conveyance system was thought to be more appropriate for the testing described here than a water-based system due to considerations of cost, risk, efficiency, and secondary waste generation.

Two types of waste simulant (sludge and saltcake) were collected with the manipulator and Scarifier. The simulants used are listed in the ACTR Technology Evaluation Test Material Recommendation, and were prepared from materials available locally:

- saltcake composition #2: 88% potassium sulfate (Dynamate brand K-Mag), 12% water
- dried sludge composition #2: 40% plaster of Paris, 22.5% pulverized kaolin clay, 37.5% water.

The saltcake was mixed in an inexpensive cement mixer; the dried sludge by hand. The tests were performed in an appropriately sized tray, which was stiff and light.

2.3.2.3 Test Results

Successful conveyance. The waste conveyance system prepared for this series of demonstrations performed successfully in that

- About 12 ft^3 of salt cake and 4 ft^3 of dried sludge were accessed by the end-effector.
- The manipulator delivered the end-effector to the waste surface.
- The end-effector cut through and fluidized the waste simulants for conveyance.
- The conveyance system retrieved the fluidized simulants and delivered the waste stream safely to storage barrels.
- Two kinds of waste simulant (dried sludge and salt cake) were used in testing.
- The arm remained fully controllable in the presence of the waste stream.
- Expensive components in the conveyance system (e.g. Scarifier, jet pump, cyclone, and blower) were by all indications undamaged by the retrieval process.

The testing was, however, ended somewhat prematurely as a result of the failure of the conveyance hose. The failure was the result of the following combination of causes:

- Holding standoff distance from the waste surface was a difficult task for the operator. With the Scarifier engaged, its water jets force the end-effector away from the waste surface, and manipulator cable tensions must be adjusted to compensate: the bottom cable of stage four, normally relaxed relative to the top cable to bear static load, must have its tension increased. As the waste surface was cleared, the end-effector was at times sucked into the waste trench and made contact with the level waste tray, forming an instantaneous seal, as the top cable did not have sufficient control authority to immediately compensate for both the bottom cable and the sucking force. This issue can be overcome in service with pressure or proximity sensors near the end-effector and their output fed back to the control system. Their output might also be used to directly activate an e-stop.

- A scalloped hard rubber shroud, used to prevent contact between the Scarifier and the waste surface while allowing the end-effector to traverse the waste surface, was not strong enough to oppose the downward pull of the vacuum force of the end-effector as the distance between the scarifier and the simulant decreased. Although this shroud was effectively held in place on the end-effector by hose clamps, and did not detach or tear, it was too compliant to provide extra standoff capability. Holes drilled into the shroud to prevent an instantaneous seal were usually covered when the shroud buckled under load. The necessity for improvements at the Scarifier-Waste interface were demonstrated during waste simulant removal testing. A number of possible solutions or improvements to the skirt have been discussed. It is essential that some type of compliance be incorporated into the skirt, either active or passive. In the case of active compliance, an additional degree-of-freedom would need to be incorporated into the skirt or shrould to provide a response time significantly quicker than the arm itself. The response time of the arm is not adequate to compensate for surface irregularities. The possibilities discussed include:

- Simple passive compliance via springs mounted in the skirt or shroud along with a contact shoe or caster to effect a compliant motion normal to the waste surface.
- A scalloped edge or other skirt design to allow proper air flow while maintaining contact with the waste surface.
- Active compliance proportional to ultra-sound surface distance feedback.
- Active compliance proportional to vacuum sensed at the skirt.
- Active compliance proportional to tactile or capacitance wisker feedback.
- Larger shroud (24").
- Higher power blower (200hp).
- Hardened CCD cameras mounted at various points on arm to provide more information to operator.

- Three 55-gallon 16-gauge steel drums, used to collect the fluidized waste simulants after retrieval, were imploded as a result of the seal between the Scarifier and the waste tray. This is not an issue, as more durable collection tanks are expected in service.

- Although an operator (with an emergency stop) was assigned to monitor the drums against failure, the e-stop could only be engaged either at the sound of the implosion or at the indication of a sudden marked drop in the rotational speed of the Scarifier. (This drop in speed immediately preceded drum implosion, as the Scarifier would become bogged down, having no freedom to rotate, immediately before sealing against the waste tray.) In either case, operator response was too late to save any of the drums. This issue can be resolved, again, with direct computer control of e-stops (though manual backups should be included for redundancy).

- The conveyance hose was not sized appropriately to withstand the seal itself once a drum had imploded. After the first drum failure, observers felt the conveyance hose had kinked somewhat, and it was splinted and rerouted to smooth its curvature. After the third drum failure, however, the hose itself flattened at two locations along its (approximately 25 feet) length, and split in several others. This is not an issue, since the sizing of an appropriate system is expected for service.

- The Scarifier was unable to achieve rotational rates of greater than 5 Hz. (It had achieved 10 Hz in testing prior to demonstration.) This was due to a malfunctioning sensor, making the Scarifier unable to recognize its own spin rate above 5 Hz. Were it able to achieve a higher percentage of its rated capability, it is likely that waste would be conveyed faster, or at least with less chance of bogging down. The demonstration could then be completed sooner, or with the conveyance of a greater amount of waste, prior to the failure of any other conveyance system components. This is not an issue, though a larger version of the Scarifier will achieve larger waste flow rates, and a stronger blower higher pressures to convey the waste.

None of the facets of this failure presents a new issue to be resolved. Their solutions are clear and clearly achievable. The life of the conveyance system can only be considered equal to the life of the weakest irreplaceable component in the system. In this case, that component was the conveyance hose, but system life could have been improved by addressing any of the problems outlined above, and improved substantially by addressing all of them.

Description of conveyance. The conveyance approach used here consisted of repeated passes of the Scarifier over the waste surface in a "windshield wiper" trajectory, which involved the use primarily of Stages Three and Four of the manipulator. After a single pass yielded as much conveyed waste as possible, the elevator, Stage Two, and the pivot were used to reposition the Scarifier for another pass over a fresh section of the waste surface. (This plan was repeated either until drum failure or until sufficient waste was removed to give the operators a good idea of system performance. Of the four trays of waste used, only one tray of salt cake did not have at least half its waste accessed by the end-effector.) Between passes, the Scarifier and high-pressure water were deactivated, and the control system operator was given an opportunity to practice the next pass and get used to the system "feel."

When the control system operator was ready, the water jets were gradually brought from city water pressure up to 30 kpsi, then the blower was activated. The high-pressure water caused the Scarifier to lift up from the waste surface, and the sucking of the blower would tend to pull the Scarifier down. The control system operator, left with no automatic means of adjusting cable tension to compensate for these two opposing phenomena, had a difficult time maintaining standoff distance. For this reason, the end-effector would spend nearly half the run time in a "dwell" waiting for the operator to be able to change direction. For this test, the dwell was not an issue, as the water jets were unable to damage the waste tray, but this observation should be checked in future generations of the conveyance system.

The Scarifier would at times get stuck on the waste surface, and the operator would need to pull both up and sideways to remove it (a result of the overly compliant shroud), and on these occasions, the manipulator would move as though plucked like a bow. This unintended impulse response revealed a manipulator natural frequency in the neighborhood of 0.5 Hz. The vibration was quickly damped out by the manipulator's couplings and by the rough motion of the Scarifier shroud. No higher-frequency vibrations were observed.

After the second pass through the third tray of salt cake, the first drum failure occurred. A trench wide enough to permit a seal had been dug in the waste tray. Failures subsequently occurred more frequently as the last salt cake, and then dried sludge, were conveyed. It is possible that some aspect of the conveyance system was compromised, though not visibly so. In the first drum failure, making the other failures occur more easily.

Figure 2-5 shows the Scarifier accessing waste in preparation for retrieval:

Figure 2-5. Scarifier above waste surface.

Data. Prior to the first drum failure, conveyance in one tray of salt cake was observed and some data recorded. In this tray, three passes were made through the waste, and the Scarifier accessed about half the waste in the tray.

- Pass duration: 4.5 min, 6 min, and 6 min (average of 5.5 min/pass).
- Portion of pass spent in dwell between sweeps: about 40%.
- Translational rate of end-effector: about 3.5 to 4 in/sec.
- Volume of waste accessed by Scarifier: about 3 ft^3.
- Volume of waste conveyed into storage drum: 0.3 ft^3.
- Volume of water used by Scarifier: 4.5 ft^3 (at 2 gal/min flow rate capability of Scarifier operating at 30 kpsi).
- Volume of water conveyed into storage drum: 3 ft^3.
- **Water/waste ratio for waste accessed by Scarifier: about 1.5.**
- **Water/waste ratio conveyed into storage drum: about 10.**

These numbers indicate a much greater water/waste ratio than was anticipated. There are several reasons to expect this:

- Waste scattered from the tray into the open test area was not measured. Neither was Since an underground storage tank presents a closed system, water is more easily scavenged and waste more thoroughly conveyed. The system can be confined further with a stiffer shroud.
- The salt cake was conveyed in small particles, no larger than coarse sand. This may be due to the (low) Scarifier spin rate, and may also mean a density increase of salt cake in the storage drum relative to what was in the waste tray. The Scarifier is rated to deliver a water/waste ratio smaller than the 10 seen in the drum.

A similar performance was seen for each of three trays of saltcake used in conveyance testing. Dried sludge conveyance was somewhat more successful in that less waste by volume was scattered from the tray (the sludge was liquified by the Scarifier before conveyance), but measurements at the storage drum were impossible to make because the drum had imploded and its contents were fully mixed. Several days after the conveyance, the sludge particles had not even begun to settle.

For an underground storage tank containing 20000 ft^3 of waste, and a conveyance system delivering the flow rates indicated here, the waste would be conveyed after about 3200 hours of service. With single-shifts for operation, that would take 20 months. A conveyance system with greater capacity would certainly perform the operation faster:

- Increase the area of the conveyance hose by a factor of two and decrease to 1600 hours.
- Increase the Scarifier spin rate by a factor of two and decrease perhaps to 1000 to 1200 hours.
- Reduce the manipulator dwell by 20% (automatic control should do better still) and decrease perhaps to as few as 800 hours.

Required head. Analysis of the conveyance system used in this testing indicated that it was possible to use the system here to convey waste with a 3-inch diameter hose, in which case the hose could have been routed through the interior of the arm. (The hose used in the test had a 4-inch diameter.) For either hose, waste could theoretically have been conveyed through a vertical distance of 20 feet, which would enable the collection of wastes in the Actuator Room. The 4-inch hose enabled waste to be conveyed through a vertical distance of 60 feet. (Issues involving safety and availability of space confined the conveyance of waste to the immediate neighborhood of the waste tray, which was well within the capability of the blower.)

The following table indicates the capability of the system given here using sludge and saltcake:

Simulant	Volume flow rate, ft^3/min			Specific weight, lbf/ft^3			Hose	Vertical	Total wt.	Exit	Head	Pressure
Type	Air	Water	Simulant	Air	Water	Simulant	diameter	lift	flow rate	velocity	Loss	drop
							in	ft	lbf/min	ft/sec	ft	psi
Saltcake	1000	0.01	0.5	0.01	60	100	4	20	60.6	24.8	11.4	0.10
Saltcake	1000	0.01	0.5	0.01	60	100	3	20	60.6	44.0	48.1	0.25
Saltcake	1000	0.01	0.5	0.01	60	100	4	60	60.6	24.8	34.2	0.26
Saltcake	1000	0.01	0.5	0.01	60	100	3	60	60.6	44.0	144.3	0.60
Sludge	1000	0.01	2.0	0.01	60	100	4	20	210.6	7.1	0.9	0.67
Sludge	1000	0.01	2.0	0.01	60	100	3	20	210.6	12.7	4.0	0.82
Sludge	1000	0.01	2.0	0.01	60	100	4	60	210.6	7.1	2.8	1.96
Sludge	1000	0.01	2.0	0.01	60	100	3	60	210.6	12.7	12.0	2.29

Table 2-2 Required head

Safety measures. The following safety measures were taken prior to waste conveyance, and were proven effective:

- At the point of operation
  - Polycarbonate shielding, secured during testing but easily movable, prevented operational interference with observations.
  - Operation of the deployment and end-effector pivot control systems was on-off and simple.

  - Power machinery was on-off and redundant e-stops were available.
  - Multiple operators were trained in the use of the Scarifier, jet pump, and blower.

- Within the conveyance system
  - Working parts were shielded.
  - Each power machine was assigned an operator with an e-stop; each operator was empowered to shut down in the event of any unexpected issues.
  - Redundant ear protection was provided for operators and observers; flashing lights and warning signs were used to limit access to the test area during conveyance.

A NIST safety officer reviewed these measures and added comments prior to operation.

There were two safety concerns during operation. First was the occasional necessity of starting the Scarifier spin by hand after it had bogged down. This was done more than once, but in each case the operator of the jet pump worked in coordination with those handling the Scarifier to ensure that high-pressure water was deactivated. Second was the elevated temperature of the blower exhaust hose, after conveyance for several minutes the hose would be too hot to touch. No one ever did touch it. A rubber hose such as that used simply is not suitable. GreyPilgrim is working with Waterjet and the blower manufacturer to improve this facet of conveyance.

3.0 ISSUE RESOLUTION

ADVANCED STAGE TESTING

<u>Conceptual Design</u>:

1. Can the manipulator long enough to do the job be considered reliable and cost-effective?

   Yes. The demonstration manipulator used for testing was 33 feet long, with 4 independently controlled and operated stages. In addition, a cable controlled adjustable mounting for the end-effector was used to keep the end-effector normal to the waste simulant.

   During the early stages of the manipulator development and detailed component set testing, detailed engineering models were developed to characterize and calculate the key variables used in designing and building the EMMA. These variables include cable tensions, coupling size and coupling stiffness. Details of this engineering data are excluded from this report and its appendices as this data are considered Company Proprietary. Information and review of this data can be obtained after mutual confidentiality agreements have been executed.

   The engineering data developed indicates that the manipulator can be built to varying lengths to optimize its utilization in a tank environment. Engineering models have been built up to 45 feet for a manipulator weighing approximately 1,000 pounds.

   Preliminary results indicate that the manipulator will be cost effective for operation in the Hanford tank environment. However, a final determination of the manipulator reliability and cost effectiveness cannot be made until final manufacturing designs and component selection have been made. This demonstration contract did not provide adequate funding or time to complete these activities. As part of the on-going development of the EMMA, the cost effectiveness and system reliability will be established prior to the next phase of the Hanford Tanks Initiative (HTI) program.

2. What is the minimum riser size required for deployment?

   The EMMA used for demonstration purposes was 24 inches in diameter with the fourth stage having an 18 inch diameter.

   Detailed engineering designs have not yet been completed for smaller sized diameter manipulators of any significant length. However, due to the simplicity of design and the engineering models completed during the building of the demonstration manipulator, it is believed that a multi-stage manipulator as small as 12 inches in diameter and at least 30 to 40 feet in length can be successfully built and operated.

3. Can sensitive components be kept out of the tank?

   Yes. The manipulator built and demonstrated by GreyPilgrim does not have any electronic or hydraulic components on the manipulator.

GreyPilgrim's demonstration manipulator was 33 feet long and consists of 4 stages, each actuated with 4 cables driven by hydraulic actuators. The manipulator consists of cables, couplings and rigid segments.

The manipulator is controlled utilizing hydraulic actuators with computer controlled force feedback controls. The hydraulic actuators, the force feedback load cell transducers, and all computers and control software are separated from the manipulator and located outside the tank environment.

4. Should the conveyance hose run through the center of the manipulator?

   The conveyance hose on the demonstration manipulator was attached to the outside of the manipulator and did not run through the center of the manipulator. This was done for two reasons. The conveyance system utilized for testing required a 4" inside diameter (ID) hose to optimize the air conveyance system. In addition current designs for hose management outside the tank appear to require the hose not go through the center of the manipulator.

   Based on testing performed during the demonstration, there is not significant dynamic stress put on the manipulator by the conveyance system. Final determination on the most effective location for the conveyance hose will be based on the overall requirements of the waste conveyance system. The manipulator will accept the conveyance hose either through its hollow center, attached to the outside of the manipulator, or as a separate system deployed through a different tank riser.

Load Bearing & Static Deflection:

5. How well does the system bear static loads caused by end-effector operation at full reach?

   No impact was noted. The manipulator was designed to carry at least a 100 pound payload. The lightweight Scarifier with hoses and single pivot attachment weighed less that 100 pounds and did not have an impact on the arm when attached.

6. How accurately can the end-effector be positioned and oriented?

   Test results indicate that an experienced operator can position a static end-effector to almost arbitrarily small accuracy for a 33-foot arm. No testing was done, however, to verify knowledge or other sources of position uncertainty.

7. Is the system dexterous enough to maneuver around in-tank hardware?

   The demonstration manipulator had 4 stages, which varied, in length and in coupling configuration. The design of the manipulator was based on the requirements and limitations (see section 2.3.2.3) of the space in which the manipulator was to operate. Detail set testing performed during the building of the manipulator indicates that each coupling has the capability to bend at least 25 degrees. Therefore, each stage of the demonstration manipulator can bend 50 degrees to 100 degrees depending on its configuration. Since each stage of the manipulator can bend independently of the other stages and can bend in opposite directions for the other stages the manipulator demonstrates a significant degree of dexterity to maneuver around in-tank hardware.

Pointing accuracy testing showed that the 33-foot arm could bypass an object as much as six inches in its path, using only two stages and the end-effector pivot.

See also video of the manipulator.

<u>Dynamic Response</u>:

8. How well does the system bear dynamic loads caused by end-effector operation at full reach?

No significant impact was noted between full operation of the end-effector and the operation of the manipulator with the end-effector turned off.

CONTROL SYSTEM TESTING

<u>Operations</u>:

9. Can the system operate under closed-loop control or is telepresence required?

   The demonstration utilized teleoperative control. It is expected that in a tank environment, continued us of telepresence would be required and utilized. Current engineering data indicates that closed-loop control is achievable, though this information is still being collected.

10. Can electronics and actuation be kept out of the tank?

    Yes. Demonstration manipulator had no electronics or hydraulics on the manipulator and none were required to operate the manipulator. The Scarifier end-effector was driven by an electric motor, which was connected, to an electronic control system outside the tank. It is expected that these components can be designed and manufactured to withstand the tank environment.

<u>Pointing Accuracy</u>:

11. Can the manipulator "know" where it is within the tank?

    Yes. Pointing accuracy test results indicate that arbitrarily small accuracy is possible. Test results for the inverse kinematics algorithm indicate that it can be integrated into an automatic control system, though its limitation is a tradeoff between computational speed and accuracy of final position. The selection of off-line v. on-line implementation is still an issue.

12. Can the manipulator be made to avoid in-tank hardware?

    Yes. Pointing accuracy test results indicate that avoidance can be accomplished in many ways.

13. Can the control system compensate for static deflection of the manipulator?

Yes. Static deflection test results indicate that compensation is well within control system capability.

Dynamic Response:

14. Can excessive vibrations, if induced during operation, be effectively isolated and attenuated by the control system?

    Yes. Test results indicate that if the control loop cuts off actuator commands, the arm will simply stop where it is. Then the stiffness provided to the arm by cable tension will damp out residual vibrations.

15. Can a known end-effector (e.g. Scarifier) be held in a desired position and orientation, and maneuvered along a desirable trajectory?

Yes. Test results indicate that the same trajectory can be repeated over and over again, and that an experienced operator can achieve efficient waste access with overlapping trajectories.

INTEGRATED RETRIEVAL TESTING

System Deployment & Insertion:

16. Can the in-tank system be delivered into the riser safely?

    The safe deployment of the manipulator system into a tank riser is described in Appendix 5.1. A simulation of this deployment was done in IGRIP and is included by reference to this report.

    The method described and simulated utilizes a RoboCrane, a three-legged crane capable of accurately and safely inserting the manipulator and any other equipment necessary into the tank. The existing 20' RoboCrane has remote handling and placement accuracy of +/- 1/8".

17. What is the height of the required deployment structure?

    The current design of the RoboCrane deployment structure is 46 feet tall. At full extension, a manipulator deployment mast would extend an additional 22 feet from the top of the crane structure. During operation, the mast would not extend beyond the top of whatever mobile crane is employed, provided it is not much shorter than the RoboCrane.

18. What structural loads are expected on a tank dome?

    The RoboCrane is a three-legged structure designed to put all loads outside the tank dome circumference.

19. What hardware is required to process waste outside of the tank?

    Reference Appendix 5.1 describing the waste retrieval system requirements.

General Retrieval:

20. What is the expected system life?

This demonstration manipulator was a prototype designed to prove the concept and demonstrate the capabilities of the manipulators dexterity and ability to retrieve waste.

It is not possible at this time to determine the life expectancy of the manipulator system. Final design and manufacturability of the manipulator are currently underway but will not be completed until the 4th quarter of 1997.

All out of tank hardware and components should have a long life and be usable over multiple tank cleaning campaigns.

21. What is the expected system cost?

While final cost of the system is not determinable at this time, several factors contribute to the conclusion that the system provides several significant cost advantages. These factors include:

- complex and expensive components remain out of tank and are easily maintained or quickly replaced.
- the in-tank components are simple, reliable, and inexpensive.
- the above-ground system is entirely reusable for subsequent work with a variety of different EMMA configurations suitable for the entire range of tank operations.
- the system is highly modular, providing easy configuration for any particular tank or task.
- the waste retrieval rate and efficient path planning require less time on tank.
- the above-ground system is mobile for efficient set-up and closure of operations.
- arm disposal in-tank may cost less than decontamination and removal.
- the arm will be able to deploy characterization end effectors, eliminating the need for a separate procurement or installation following tank waste retrieval operations.

The final design of the total system has not been determined and will be a function of the prime contractor designing, installing and operating the system and, therefore, the cost of the manipulator and control system has not been determined.

22. How long can the system operate before requiring maintenance?

Reference Appendix 5.1, section 1.5 of the report describes expected maintenance requirements.

As indicated above, the manipulator system design has not yet been finalized. Therefore, maintenance requirements are not determinable.

23. Is it cost-effective to jettison a manipulator after failure or completed mission?

While the final system design has not been completed, the manipulator is expected to be inexpensive, and disposal is expected to be less costly than decontamination procedures necessary to remove and decontaminate the manipulator either at failure or completion of the tank campaign. Final determination will be made during the completion of the final design and manufacture of the manipulator.

24. How will the retrieval system compensate for working in a flammable atmosphere?

    It is expected that a partner with experience in waste retrieval will develop a system that addresses the issue of the flammable environment.

25. What is the required head of the retrieval system?

    The retrieval system used here requires a minimum of 150 ft of head to convey waste through a vertical distance of 60 ft. It is likely that this performance is achievable with a stronger blower and larger Scarifier and conveyance hose.

<u>Specific Retrieval Demonstration</u>:

26. Can the system bear dynamic loads caused by waste flow when the manipulator is at full reach?

    Yes. Test results indicate that the arm and deployment elevator were undamaged by waste flow, and that excessive vibrations in the structure were not evident. The failures experienced were due to a strong vacuum seal when the end-effector contacts a bare surface, and are fully correctable.

27. What retrieval rates are achievable?

    Test results indicate that the end-effector can be made to travel at 4 inches/sec or more to access the waste. Retrieval rates are given in this report, but are considered biased by the Scarifier not performing fully to specs, and by the test area not being closed and allowing waste to scatter all around the arm.

28. Can water introduced to the tank by retrieval operations be fully scavenged?

    In this test, water not scattered outside of a waste tray was fully accessible and thus could be scavenged. In service, however, containment of water can be easily achieved through the use of a stronger shroud and blower.

29. Can waste be conveyed safely?

    No safety concerns are currently known that were not addressed prior to retrieval.

30. What maximum size of waste particles can be conveyed?

Again, the scatter of waste and Scarifier performance bias this result, but the largest particles actually conveyed were the size of coarse sand.

3.1 Issues Not Resolved With Demonstration and Testing

The following issues remain open and were not resolved with the testing and demonstrations performed under this contract:

1. What is the expected system life?
2. What is the expected system cost?
3. How long can the system operate before requiring maintenance?
4. Is it cost-effective to jettison a manipulator after failure or completed mission?

Due to the limited scope of the funding and time period of the contract, these issues have not been resolved as of the completion of the demonstration and testing. These issues will be addressed during the continued development of the EMMA system referred to in section 4 of this report.

4.0 DISPOSITION OF TEST MANIP ULATOR & RETRIEVAL SYSTEM

GreyPilgrim retains the prototype EMMA manipulator and the control system used in this demonstration for use in the continued development of the manipulator and control system technology. Schilling Robotics has agreed to work with GreyPilgrim to provide a manufacturability study to assist in the conversion of the prototype into a finished product. This work will continue at NIST and with Schilling Robotics, Inc. as to convert the prototype system into a viable commercial product for use at Hanford, other DOE sites and in the commercial market place.

The Scarifier used has been returned to Waterjet Technology, Inc.

The 36-kpsi Jet Edge Model 36-250D pumping unit and ultra high-pressure hose was rented from WaterBlasters, Inc. and has been returned. The other components within the conveyance system, the blower, cyclone and hoses, were purchased by GreyPilgrim and will be utilized in the continued development of the waste retrieval capabilities of the EMMA system.

5.0 APPENDIX

5.1 BNFL Report Describing Conveyance System.

This report has been submitted under separate cover along with hardcopies of this report.

EASILY MANIPULATED MECHANICAL ARMATURE (EMMA) WASTE RETRIEVAL SYSTEM

MAY 28, 1997

Prepared By:
BNFL Inc.
Richland, Washington

Prepared For:
GreyPilgrim LLC
Orange, California

TABLE OF CONTENTS

LIST OF FIGURES

ACRONYMS

ALARA	As low as reasonably achievable
DST	Double-shell tank
EMMA	Easily Manipulated Mechanical Armature
HEPA	High-efficiency particulate air (filter)
HVAC	Heating, ventilating, and air-conditioning
ISO	International Shipping Organization
PHMC	Project Hanford Management Contractor
RCRA	Resource Conservation and Recovery Act
SST	Single-shell tank

EMMA RETRIEVAL SYSTEMS CONCEPT REPORT

1.0 RETRIEVAL SYSTEM CONCEPTS

1.1 OVERALL SYSTEM CONCEPT

An easily manipulated mechanical armature (EMMA) system has been proposed to retrieve waste from a Hanford single-shell tank (SST). The remotely operated, cable driven serpentine arm has a long reach and considerable dexterity. The arm is constructed of multiple stages, each equipped with an independent set of cables, allows the arm to make complex curves. When equipped with an end-effector, such as a scarifier, the system will be able to remove hardened tank waste. The arm is hollow, allowing fluid delivery to the scarifier and removal of waste slurry from the tank. For tanks with small diameter access risers, the scarifier system can be deployed through a separate riser and picked up by the EMMA system in-tank.

1.2 SYSTEM RETRIEVAL APPLICATION AND TANK ACCESS

The following sections address how EMMA will access the tank interior and accomplish waste retrieval.

1.2.1 Construction

Prior to deploying the EMMA apparatus on a tank, construction of tank farm modifications will be necessary. The extent of modification will be dependent on which tank is selected as the demonstration tank for Hanford tank initiative, but may include installation of a temporary ventilation system. The ventilation system will include a demister, water knockout drum, heater and high-efficiency particulate air (HEPA) filtration, and will be utilized to remove heat from the tank, provide ventilation, and recycle moisture resulting from misting during scarifier operation. The construction of two double contained underground waste preparation tanks, equipped with leak detection and mixing capabilities, will provide the ability for batch transfer to double shell tanks (DST) along with the ability to settle out solids and recycle supernatant. A third preparation tank may be required to allow for solid settling. Tanks can only be sized once the retrieval rate from the scarifier is known. Both underground preparation tanks will be located in the tank farm so that reuse of these tanks is possible for future retrieval projects of remaining SSTs in the specific farm. The underground double contained scarifier feed tank, equipped with leak detection, will provide recycle of supernate to minimize waste generation for ongoing scarifier activities. The addition of raw water will be provided through a designated line as a make-up when needed. Pneumatic pumps will provide pumping of material between tanks and transfer to a DST. A temporary compressed air system will be installed to drive these pumps. In-tank cameras and lighting will be installed to support operations and ensure clean-up is complete. If camera systems alone are not adequate to guide the armature, an electronic mapping system will be required. Figure 1-1 provides a conceptual detail of retrieval equipment and the associated piping transfer layout. Figure 1-2 provides a top view of tank penetration points and additional equipment requirements necessary for tank waste retrieval.

Figure 1-1. Tank Waste Retrieval Conceptual Design and Equipment

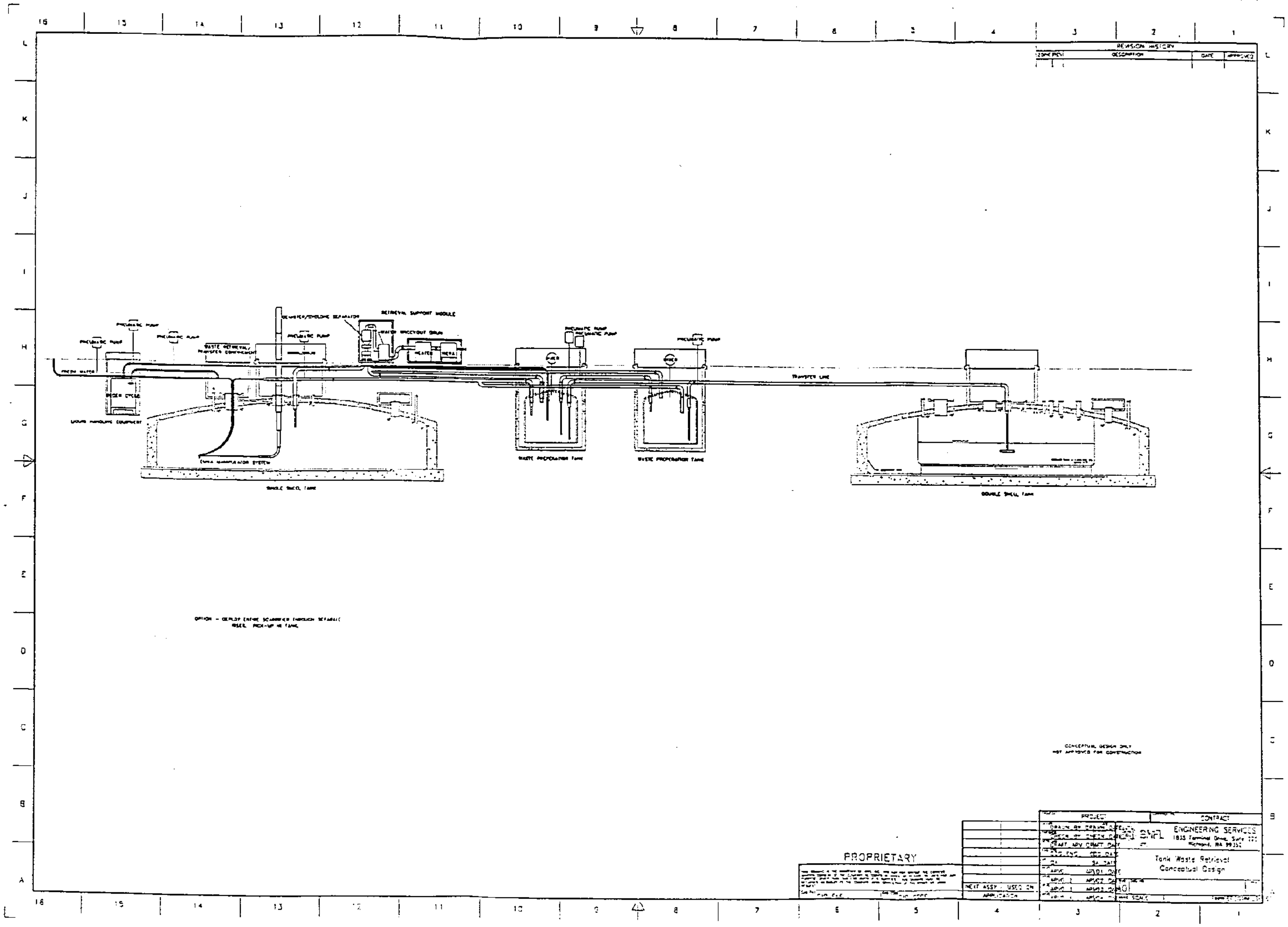
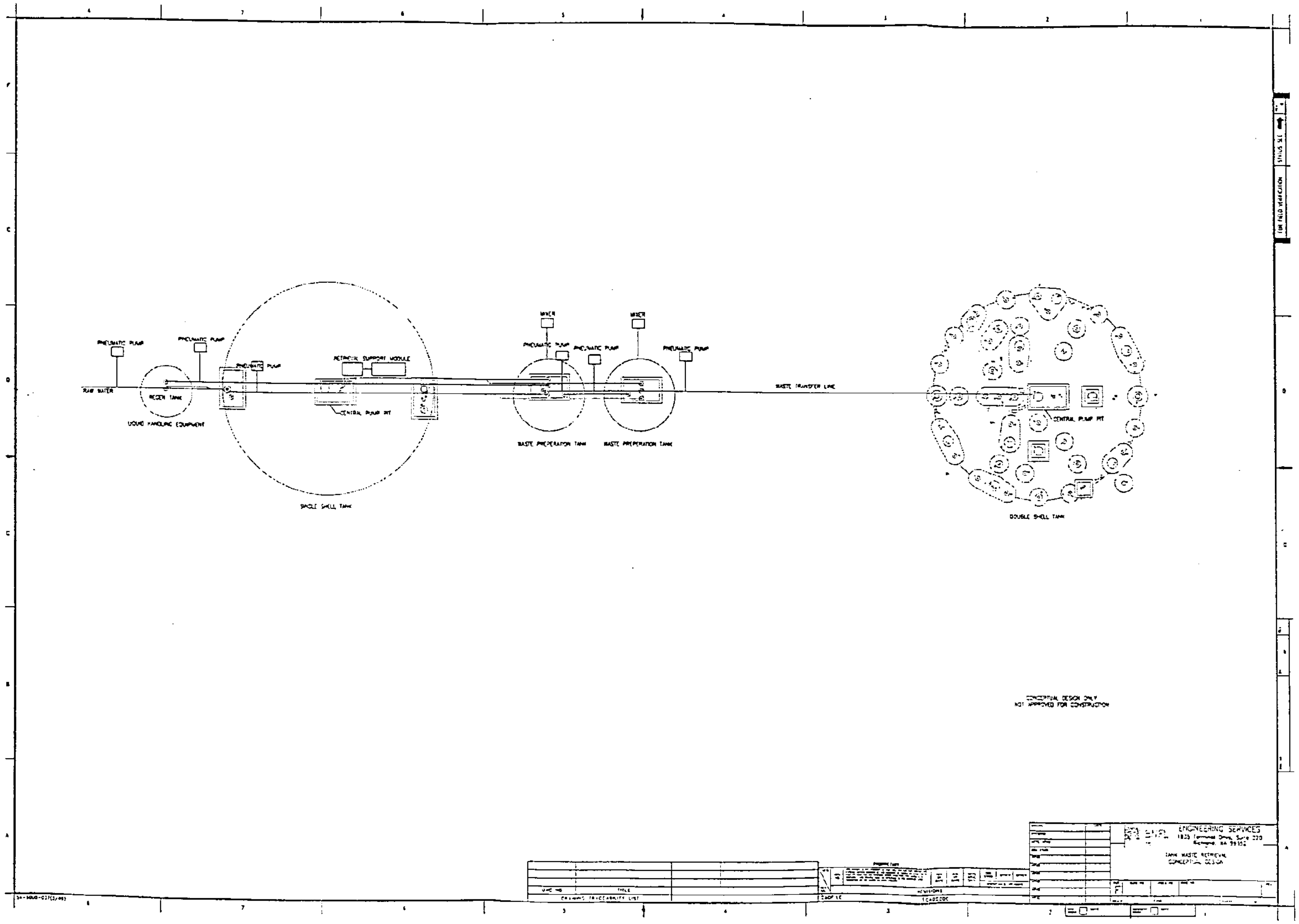


Figure 1-2. Tank Waste Retrieval Conceptual Design and Equipment



Prior to construction modification, existing in-tank and out-of-tank waste retrieval equipment and extraneous in-tank hardware that are occupying tank access risers will have to be removed, and returned to the operations contractor for treatment and disposal. The equipment must be decontaminated during removal to minimize personnel exposure and waste disposal quantities. The operating contractor has equipment specifically designed for the removal of items from the Hanford tanks and tank pits. It is recommended that this task is subcontracted to the Project Hanford Management Contractor (PHMC).

Following equipment removal, the pump and sluice pits must be decontaminated and prepared for new equipment installation. Existing pit nozzles and penetrations will be used where possible. All activities over and in the pits will require remote access techniques to maintain operator exposures as low as reasonably achievable (ALARA).

Any contamination of the tank farm surface must then be cleaned up, and the surface returned to a safe, stable condition.

1.2.2 Installation

Once construction of the support facilities is complete, the EMMA apparatus will be installed. The current design shows a three-legged RoboCrane to suspend and lower the arm into the tank. The maximum height of the crane platform, which is raised and lowered using cables, is 46 feet 8 inches. A torque-resistant mast will extend 22 feet above the platform. The purpose of the mast is to secure and stabilize the manipulator arm. The manipulator arm cable drive and control equipment will be housed in an International Shipping Organization (ISO) container installed on the crane platform.

A flexible confinement enclosure will connect the EMMA platform to the tank riser or pump/sluice pit. The enclosure will collapse as the system is lowered into the tank and unfold as the system is retracted. Water wash-down spray rings will decontaminate the in-tank hardware during removal of the EMMA apparatus.

The tank pump or sluice pits and cover blocks will be modified to provide access to remotely remove the riser plug and connect the confinement enclosure. Total tank confinement must be maintained during this confinement boundary modification. Adequate cover blocks (or functional equivalent) must be maintained to provide the safety boundary for waste transfer operations.

The crane's legs will be equipped with crawler tracks for movement. Control equipment for the crane tracks, the crane platform, and the EMMA will be installed in an ISO container at grade level. The circumference inscribed by the crane tracks will be larger than the 75 foot tank diameter. The position of the legs will be evaluated prior to installation to ensure that the candidate tank and adjacent tank load limits are met, and the crawler can navigate through the tank farm to reach the intended tank.

Utilities, piping, and control connections will be completed. All waste preparation and transfer equipment will be located below grade level for shielding and to minimize obstructions. If installed on a central riser, EMMA will be able to reach all waste surfaces. If not on a central riser, the arm will need to be retracted and re-inserted through additional risers to complete its task. Risers greater than 12 inches in diameter are needed for installation of the arm plus conveyance hose. In the case that only a 12 inch riser is available the conveyance system hose can be separated from the manipulator arm and deployed through a separate riser. (Note: C-106 central riser is only 12 inches with one non-centrally located riser larger than 12 inches.)

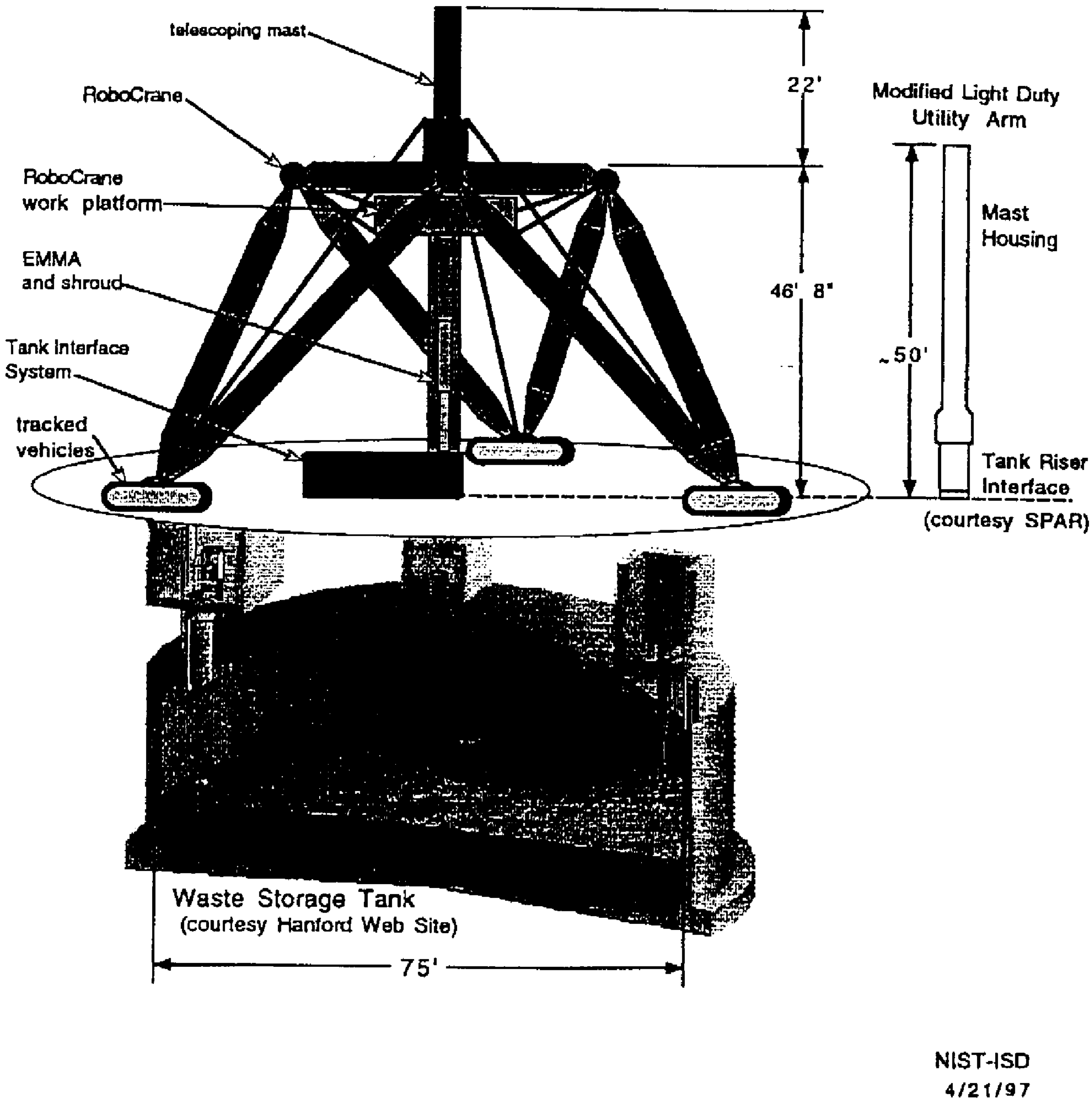
The RoboCrane is one option for deployment into the tank. The RoboCrane provides the potential for remote handling and insertion of the EMMA system, but it is not the only method of deployment and the two systems are not permanently linked together (See Figure 1-3).

1.2.3 Operations

The correct installation and reconfiguration of the tank safety/confinement boundary will be verified. Lighting and camera equipment will be activated. If needed, mapping equipment will be activated. The EMMA arm and scarifier will be lowered through the confinement enclosure into the tank. Utilities and piping connections will be completed. The following steps will occur:

- The tank ventilation system will be verified as operating properly to maintain air-borne radioactive material confinement, remove moisture, and to filter air from the tank and support equipment.
- Leak detection systems for the piping and support equipment will be verified as operable.
- The EMMA arm will be lowered to the waste surface to acquire and connect to the waste scarifier.
- The pneumatic retrieval transfer pump will be started.
- The scarifier will be started using raw water (or recycled waste supernatant, if available).
- Retrieved waste will be pumped to one of two new underground, double-contained, waste preparation tanks.
- As retrieval continues, the arm will be moved as needed around obstacles in the tank.
- The waste accumulated in the preparation tanks will be evaluated versus criteria for pumping and acceptance in the receiving DST. Excess supernatant will be recycled to a scarifier feed tank. The preparation tanks will be equipped with mixers to suspend solids, with sampling capability, and with the ability to add process chemicals, such as sodium hydroxide and sodium nitrite. Conditioned waste will be verified to be within DST acceptance criteria prior to transfer.

Figure 1-3. Waste Storage Tank Remediation System.



- Retrieved and conditioned waste will be pumped through an underground pipeline to the receiving DST.

- The EMMA arm may be detached to be disposed as in-tank hardware, or it may be flushed and retracted for re-use in another riser or on another tank. If the arm is to be retracted from the tank, the waste scarifier will be released and left in-place. The exterior of the arm will require flushing to reduce the dose rate to operations personnel and minimize potential for contamination spread. Containment on the outside of the arm, such as a double sleeve or jacket, will be provided to prevent dispersal of contaminants when the arm is outside of the flexible confinement enclosure.

1.3 APPROACH TO CONTROL AND MONITORING

Several control and monitoring systems will be used during waste retrieval. These systems include the following.

1.3.1 Area Radiation Monitors

Area radiation monitors will be used to detect elevated radiation in the vicinity of EMMA operations. Use of these monitors will provide a visible and audible warning to site personnel.

1.3.2 Ventilation

EMMA operations will require active ventilation of the candidate tank and supporting facilities. Alarms and interlocks will be provided to prevent operation of the retrieval system without adequate ventilation. The ventilation system will draw air into the tank and provide de-entrainment of moisture droplets and HEPA filtration of suspended particulates. A heater will warm the vapor prior to filtration to protect the filters from condensation. Stack discharges will be monitored and sampled. Indicators and alarms will be included to verify adequate operation and warn of problems. The existing ventilation system will be used if confinement capacity and filtration efficiencies are adequate.

1.3.3 Cameras and Lighting

Cameras and lighting will be required to support operation of the EMMA arm. The tank interior and waste surface must be visible for accurate arm movement. These systems will be installed through tank risers and controlled using electric motors. Controls for this equipment and display terminals will be located at grade level along with the EMMA retrieval system controls. An arm-mounted camera/light system will be included for direct viewing of the end effector operation. If acceptable visibility cannot be obtained using camera systems, an electronic mapping system will be established to guide the armature.

1.3.4 Crane Positioning

The Robocrane is mobile, having three diesel driven tractor crawlers. These crawlers will be controlled from a master controller which will be used to coordinate tractor movements. The crane is capable of being moved on uneven surfaces, along with having the ability to pivot on its own axis. Crane leg positions will be visually verified and the route for each leg will be pre-selected to avoid obstacles during installation.

1.3.5 Crane Platform Control

The crane platform will be raised and lowered as needed to deploy the EMMA arm. The platform will use electric or hydraulic winches remotely controlled, which will be designed to fail in a safe manner. The elevation of the EMMA arm will be monitored, with absolute arm positioning feedback for a sensor ring located near the riser with alarms for unacceptable positions.

1.3.6 Jumper Installation

The waste scarifier system will be lowered into the tank from one of the risers in the service pits. The piping connections to the water supply and for waste removal must be completed. Remotely installed jumpers will be used to connect the scarifier piping to piping in the service box or pump pit. Remote capabilities will be required, since the system will become contaminated. Pits and jumpers will be equipped with flushing capability.

1.3.7 EMMA Deployment

EMMA will be deployed into the tank when it is lowered through a riser by a moveable crane platform. A flexible confinement enclosure will connect the crane platform to the riser. The deployment will be monitored using the lighting and camera system and electronic mapping system, as needed. Operation of the crane platform will not be allowed unless the tank ventilation system is operating properly.

1.3.8 Scarifier Operation and Water Supply

The scarifier will be interlocked so that it cannot operate unless the pneumatic retrieval pump is operating. The flow rate of water delivered by the scarifier will be controlled so that it does not exceed the capacity of the pneumatic pump. Raw water supply will be equipped with back flow prevention.

1.3.9 In-Tank Conditions

The tank being retrieved will be monitored for accumulation of liquid and for vapor space depression. Temperatures will be monitored as needed, particularly if the tank has a high rate of heat generation, including heat generated by the retrieval system.

1.3.10 Scarifier Liquid Handling Tanks

The scarifier system will have a raw water source line and a booster pump and a double-contained feed tank for recycled supernatant (if needed). The tank will be monitored for liquid level. The recycled supernatant tank will be vented through the portable HVAC system and be monitored for tank depression. Back flow prevention will be used to prevent contamination of the raw water line and booster pump. A booster pump may be utilized to ensure required pressure for scarifier equipment needs.

1.3.11 Preparation Tanks

Preparation tanks will be monitored for liquid and solids levels. If supernatant is to be recycled, one preparation tank will be used for settling and decanting while waste in the other tank is being sampled, treated (if necessary), mixed, and pumped to the DST. The roles of these tanks may then be reversed. The preparation tanks will be ventilated by the portable HVAC system. Tank temperatures, and mixer operation will be monitored. A material balance will be maintained to account for the volume of water added to the SST and for the amount of waste removed, to permit early indication of leaks from the SST. Preparation tanks will be equipped to handle chemical additions.

1.3.12 Transfer Pumps and Piping to DST and Scarifier Feed Tank

Transfers to the DST from the preparation tanks will be accomplished on a batch basis. Each preparation tank will have a designated pneumatic transfer pump along with decanting pumps. Transfer pumps will move waste to the DST. Decanting pumps will recycle supernatant to the scarifier feed tank. The mixer in the feed tank will be activated and operate continuously during the transfer to the DST. Liquid levels, temperature, and tank depression will be monitored. The level in the receiving tank and any potential interconnecting tanks will be monitored for material balance purposes as well as to detect any potential misrouting.

1.3.13 Leak Detection

All process piping outside of the SST will have secondary containment and leak detection instrumentation. The preparation tanks and scarifier feed tank will also have double containment and leak detection instruments.

1.3.14 Process Drains

Drainage from process pits and pipe leaks will be directed to the waste preparation tanks.

1.4 INTERFACES WITH HANFORD SERVICES AND INFRASTRUCTURE

Hanford services and infrastructure include site roads and tank farm access; raw and sanitary water supplies; electricity; steam; compressed air; SST farm instrumentation, leak detection, surveillance, and operations; change rooms; Resource Conservation and Recovery Act (RCRA) and Clean Air permits; safety, emergency response, and fire protection programs; and solid waste disposal. Services required by the EMMA retrieval system are addressed in the sections that follow.

1.4.1 Site Roads and Tank Farm Access

Construction and installation of EMMA systems will require use of Site roads and access to tank farm areas. Construction supplies are expected to be delivered by truck. A construction lay down area and equipment assembly area will be established adjacent to the tank farm. Transfer of equipment into radiologically controlled areas may require the use of Site transport equipment and personnel. Surveys of vehicles leaving radiologically controlled areas and monitoring of work activities are assumed to be performed by Site radiation protection personnel. Construction personnel will require training for radiation work.

1.4.2 Raw and Sanitary Water

The EMMA retrieval operations will require a raw water supply for scarifier operation and for flushing equipment and piping. As a result, some piping modifications to the existing raw water system may be needed. Sanitary water will not be needed.

1.4.3 Electricity

An electrical supply will be needed to operate the Robocrane platform, crawler tractors, EMMA system, scarifier, instrumentation, transfer pumps, tank mixers, and portable ventilation system.

1.4.4 Steam

Steam is not expected to be required for EMMA operations.

1.4.5 Compressed Air

Pneumatic instrumentation is not expected to be used in support of EMMA operations, so an instrument air supply will not be required. A skid mounted air supply system will be provided to operate the pneumatic pumps.

1.4.6 SST Farm Instrumentation, Leak Detection, Surveillance, and Operations

Current Site programs for SST tank farm surveillance, maintenance, operations, and leak detection are expected to be maintained.

1.4.7 Change Rooms

Existing change rooms are expected to support EMMA construction and operations personnel.

1.4.8 RCRA and Clean Air Permits

A modification to the Tank Farms Part B Permit Application may be needed to include the EMMA system and waste preparation tanks. An interface control document will be required to formally identify the requirements to be met in order for the waste to be accepted in the DST farms.

The Hanford Site Air Operating Permit will require modification to include emissions from the HVAC system stack.

1.4.9 Safety, Emergency Response, and Fire Protection

New or amended safety analysis documentation must be prepared to include the EMMA retrieval system in the tank farms safety basis. Emergency plans and a fire hazards analysis will require preparation or amendment. Emergency response and fire protection are expected to be supplied by existing Site forces.

1.4.10 Solid Waste Disposal

Construction and operation of the EMMA retrieval system will generate solid wastes. Disposal of non-hazardous, hazardous, low-level, and mixed waste is expected to be handled through existing Site facilities.

1.5 MAINTENANCE AND DECONTAMINATION PROVISIONS

No routine maintenance activities are expected for the EMMA arm.

Maintenance for the RoboCrane deployment platform and crawlers are expected. All of this work is expected to be in place without removing the EMMA arm from the tank.

Maintenance alternatives for unexpected component failures on the EMMA arm include removing the arm from the tank to a radiation protection area maintenance shop, or replacing the entire arm with a new one. Contact maintenance would require significant decontamination and reduction in dose rate.

The arm will be encased in a double flexible sleeve or jacket, which will prevent accumulation of radioactive contamination on the equipment surfaces. The outer sleeve will be removed from the arm as the arm is lifted from the tank to prevent release of airborne contamination. The discarded sleeve will be disposed as solid waste. All surfaces exposed to tank waste, such as the scarifier end effector, will be designed to prevent the waste from adhering and to minimize crevices. The arm and the scarifier will be designed to be left in the tank at the end of the retrieval campaign, if acceptable for tank closure.

The in-tank scarifier will be designed to allow abandonment if a failure occurs. If allowed, the scarifier would be decoupled from the support systems above grade using remote access techniques. A new scarifier would then be lowered into the tank to resume waste retrieval operations.

Maintenance of all waste handling equipment will require remote maintenance techniques. Provisions will be made to flush any process piping associated with the waste transfer system. Numerous options exist, including simple component replacement at failure or rework at a suitable hot-maintenance shop.

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